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14. ABSTRACT
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15. SUBJECT TERMS
dehydration, fluid balance, strength-to-mass ratio, jump performance

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ORIGINAL ARTICLE

Hypohydration reduces vertical ground reaction impulse but not jump height

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Abstract This study examined vertical jump performance using a force platform and weighted vest to determine why hypohydration ($\sim$4% body mass) does not improve jump height. Measures of functional performance from a force platform were determined for 15 healthy and active males when euhydrated (EUH), hypohydrated (HYP) and hypohydrated while wearing a weighted vest (HYP_v) adjusted to precisely match water mass losses. HYP produced a significant loss of body mass [-3.2 ± 0.5 kg (-3.8 ± 0.6%); $P < 0.05$], but body mass in HYP_v was not different from EUH. There were no differences in absolute or relative peak force or power among trials. Jump height was not different between EUH (0.380 ± 0.048 m) and HYP (0.384 ± 0.050 m), but was 4% lower ($P < 0.05$) in HYP_v (0.365 ± 0.52 m) than EUH due to a lower jump velocity between HYP_v and EUH only ($P < 0.05$). However, vertical ground reaction impulse (VGRI) was reduced in both HYP and HYP_v (2–3%) compared with EUH ($P < 0.05$). In conclusion, this study demonstrates the failure to improve jump height when HYP can be explained by offsetting reductions in both VGRI and body mass.

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Introduction

A reduction in body mass, without equivalent losses of strength or power, increases the strength-to-mass ratio (S/M) and should improve performance in sporting events where body mass is the principle form of gravitational resistance (Harman 1994). The S/M is, therefore, critical in explosive, body mass-dependent track and field events such as high jump, long jump, triple jump, and pole vault (Viitasalo et al. 1987; Williams 1998). But it is also of importance for weight class sports where greater strength or power confers an advantage against a competitor of the same body mass, such as wrestling (Williams 1998; Kraemer et al. 2001). It is additionally relevant to any sport where jumping plays a major role, such as basketball and volleyball (Hoffman et al. 1995). The precise balance between losses in body mass and losses in strength or power will decide whether or not a performance advantage is realized. However, it is important to recognize that relative performance may be improved by losses of both so long as there is a net increase in the S/M.

Gradual losses of body mass (over days or longer) achieved with energy and fluid restrictions usually result in losses of lean tissue mass, fat mass, and water mass (Nindl et al. 2002; Welsh et al. 2008). Gradual mass losses appear to reduce strength and power of the leg extensor muscles (Nindl et al. 2002; Welsh et al. 2008) but produce no effect (Fogelholm et al. 1993), or substantially impair (Chicharro et al. 1998; Welsh et al. 2008) vertical jump performance. This reflects that the trade-off between lost strength and lost mass yields no gain in S/M and provides no jumping advantage; it may even have a detrimental effect. However, acute (hours) losses in body water mass (hypohydration), which are not confounded by energy deficits or losses of contractile protein, may possibly preserve or even improve the S/M. Critical reviews (Fogelholm 1994; Judelson et al. 2007a) of hypohydration's effect on strength and power, independent of body mass, indicate a small negative impact (1–3%) which might not appreciably reduce the S/M.

Acute hypohydration clearly does not impair vertical jump performance (Gutierrez et al. 2003; Hayes and Morse 2009; Hoffman et al. 1995; Judelson et al. 2007b; Viitasalo et al. 1987; Watson et al. 2005), but it remains uncertain why only one study (Viitasalo et al. 1987) has ever confirmed the expected improvement in jump height that should accompany a reduction in body mass. Acute hypohydration should increase jump height, provided that muscle contractile function remains normal, because gravitational and inertial resistance to jumping are proportional to body mass (Harman 1994; Appendix). Since the net balance between losses in mass and strength or power will determine whether or not jump height is increased, decreased, or unchanged by hypohydration, seemingly small reductions in strength or power (Judelson et al. 2007a) are presumably enough to mask the benefits of a lighter body mass when jumping.

Although the effects of hypohydration on motor unit activation have received some attention (Bigard et al. 2001; Evetovich et al. 2002; Hayes and Morse 2009; Judelson et al. 2007b), none of the methodologies thus far studied offers insight toward understanding the reasons for impaired vertical jumping. The large osmotic stress ($\sim$300 mmol/kg) that commonly accompanies hypohydration from sweat loss (Feig and McCurdy 1977; Kraemer et al. 2001) can modulate opening of the blood–brain barrier (Rapoport 2000), alter neuronal firing of hypothalamic osmoreceptor cells (Boulant and Silva 1988), and plausibly affect excitability of motor output pathways (Enoka and Stuart 1992). The kinetic impulse (time integrated moment of force or momentum) in the initial phase of muscle contraction ($\sim$30 ms) may be affected by motoneuron recruitment and firing frequency (Aagaard et al. 2002). Because it takes the knee extensor muscles comparatively longer ($\geq$300 ms) (Thorstensson et al. 1976) to reach peak force than the muscle contraction times associated with rapid jumping (50–200 ms) (Aagaard et al. 2002), faster force development in the propulsion phase of jumping is important for maximizing jump height (Harman et al. 1990). The product of applied force and time during the propulsion phase of jumping, or the vertical ground reaction impulse (VGRI), directly impacts jump height as it is equivalent to the change in momentum (product of mass and velocity) of the total body center of mass (TBCM) (Cordova and Armstrong 1996; Harman et al. 1990). Any link between osmotic stress, neural motor unit activation, and jump height might therefore be inferred by quantifying VGRI during a vertical jump test with and without changes to hydration state (body mass, plasma osmolality).

Although practical tests of jump performance (e.g., measured distance, flight time) have been the standard for hypohydration studies, the confounding effects of mass on acceleration (acceleration = force/mass) require separate performance tests of the leg extensor muscles that are independent of body mass (Gutierrez et al. 2003; Hayes and Morse 2009; Hoffman et al. 1995; Judelson et al. 2007b; Viitasalo et al. 1987; Watson et al. 2005). A more sophisticated means of measuring vertical jump height is to use a force platform (Hayes and Morse 2009). By analyzing ground reaction forces, kinetic and temporal variables produced by force–time curves can be used to determine the vertical position and velocity of the TBCM (Bosco et al. 1983; Cordova and Armstrong 1996; Harman et al. 1990). Force platforms also provide the advantage of linking functional performance (jump height) to instantaneous measurements of force made during natural motion (functional strength testing) (Aagaard et al. 2002; Cordova and Armstrong 1996) and afford important calculations (power, velocity, VGRI) necessary for determining precisely how hypohydration might affect vertical jump performance. Importantly, if mass could be held constant while remaining hypohydrated (HYP), such as with a weighted vest, insight might be gained into the potential independent effects of mass changes on the S/M during a vertical jump.

This study examined vertical jump performance using a force platform in an effort to determine why hypohydration ($\sim$4% body mass) does not improve jump height (Gutierrez et al. 2003; Hayes and Morse 2009; Hoffman et al. 1995; Judelson et al. 2007b; Viitasalo et al. 1987; Watson et al. 2005). In one trial, a weighted vest was used to offset body mass losses from the water deficit, thus holding mass constant in the S/M. Our hypothesis was that hypohydration would impair vertical jump height when mass was replaced using a weighted vest. Conversely, without the vest, the reduction in mass would likely mask any impairment in jump height due to some combination of offsetting strength and mass changes.

Methods

Subjects

Fifteen male subjects volunteered to participate in this study. All volunteers passed the Army Physical Fitness Test within the previous 6 months and received a general medical clearance prior to participation, thus all were considered physically fit and healthy. Use of alcohol, dietary supplements, and any medication were prohibited. Subject characteristics taken on the first day of the study were [mean ± SD (range)]: age 24 ± 5 (18–37) years, body mass 84.5 ± 11.9 (66.0–107.5) kg, height 1.78 ± 0.05 (1.69–1.86) m, body fat 16.5 ± 4.0 (10.7–25.9)%, and VO_2peak 47.0 ± 8.7 (37.4–52.4) ml/kg min. Volunteers were blinded to the study hypothesis. The US Army Research Institute of Environmental Medicine Human Use Review Committee approved this study. Subjects were provided informational briefings and gave voluntary, informed written consent to participate. Investigators adhered to AR 70-25 and US Army Medical Research and Materiel Command Regulation 70-25 on the use of volunteers in research.

Preliminary testing

Two weeks before experimental testing, anthropometric and fitness measurements were made to characterize the study population. Peak aerobic power (VO_2peak) was determined using an incremental cycle ergometer protocol with continuous gas exchange and body fat was estimated from three-site skinfold measurements (Jackson and Pollock 1978).

All volunteers completed preliminary testing over a 2-week period in a temperate environment (20–22°C) prior to experimental testing. To achieve euhydration, volunteers were given ~30 ml/kg of fluid-electrolyte beverage to consume after 1800 hours each evening supplemental to daily ad libitum fluid intakes (Armstrong et al. 1998). Ten volunteers reported to the laboratory for nude body mass measurements each of ten mornings after an overnight fast (~8 h). The remaining five volunteers reported between three and five times due to schedule conflicts. An average of the first morning nude body mass measurements was calculated for each volunteer and used as a baseline reference (Cheuvront et al. 2004) for later euhydrated (EUH) body mass determinations.

All volunteers performed between 3 and 5 practice days of vertical jump testing to reduce training and learning effects. Practice trials were designed to mimic experimental testing in every way except for heat exposure. Each day began with a 5-min warm-up on a cycle ergometer where pedal cadence was self-selected against a constant 50 W workload (Lode Corival, The Netherlands). Volunteers then performed three practice countermovement jumps from the floor. Briefly, the starting position for all jumps was an upright posture with the hands positioned to remain on the hips for the duration of the jump to allow assessment of lower extremity functional strength only (Aagaard et al. 2002; Cordova and Armstrong 1996; Harman et al. 1990). Feet were positioned at approximately shoulder width and the depth of the countermovement (degree of knee bend) was self-selected naturally between approximately 45° and 90° with the simple goal of jumping as high as possible (Harman et al. 1990). Volunteers next performed a countermovement jump from a 660 × 660 × 60 mm dual force plate platform (Leonardo v3.07, Orthometrix, Inc.) connected to a PC for the purpose of collecting force data and calculating jump height (described below). Subjects stood still on the platform with one foot on each force plate for approximately 10 s while a stable body mass measurement was made. A 3-s countdown followed after which a maximal countermovement jump was performed. Volunteers then remained standing on the platform briefly before stepping off for a 1-min recovery. This procedure was repeated three times and the highest single jump height of the day was recorded. A performance coefficient of variation (CV) was calculated [(SD/mean) × 100] using the highest jump height from the force platform determined on each of the 3–5 practice days.

Vertical jump height and all other jump performance parameters were determined from force plate data using proprietary analytical software (Leonardo v3.07, Orthometrix, Inc.). Body weight, measured while the subjects stood still, allowed acceleration of the TBCM to be calculated at each movement sample point (800 Hz). The force used to calculate the body's vertical acceleration was the vertical force reading from the force platform minus body weight. The integral of acceleration over time is equivalent to the velocity of the TBCM, and the product of velocity and force gives power. The integral of the velocity over time is equivalent to the change in vertical position of the TBCM (i.e., jump height). Because impulse is equivalent to change in momentum, VGRI (integral of force over time) was calculated as the product of body mass and the change in jump velocity (Cordova and Armstrong 1996; Harman et al. 1990). Jump height was calculated using the principle that potential energy (body weight × jump height) equals the change in kinetic energy ($0.5mV^2$, where m is the body mass in kg and V is the vertical takeoff velocity in m/s determined by the integration of vertical acceleration over time while the feet are in contact with the force platform). Jump height using the Leonardo (v3.07, Orthometrix, Inc.) was recently (Frykman et al. 2009) validated using precise motion analysis software and was significantly more accurate than typical jump and reach methods for assessing vertical jump height. Both relative measures of force (N/kg) and power (W/kg) were examined to characterize and control for any inherent bias in absolute measures (e.g., N, W) owing to the purposeful manipulation of body mass and the relationship: acceleration = force/mass. All jump measures are instantaneous maximums calculated during dynamic motion.

Experimental trials

Two experimental trials (EUH and HYP) were completed in counterbalanced, crossover fashion separated by 3–11 days. Volunteers were always tested at the same time of day, instructed to limit physical activity for 24 h, and drink ~30 ml/kg of fluid-electrolyte beverage supplemental to ad libitum fluid intakes the evening prior to testing (Armstrong et al. 1998). Volunteers were overnight fasted (~8 h) upon arrival to the laboratory. Nude body mass was measured for all volunteers (±50 g; Mettler Toledo, Model WSI-600, Toledo, OH). Both before and after heat exposure, a subset of 10 volunteers sat for 20 min to allow fluid compartment stabilization prior to collecting a 7-ml venous blood sample for determination of plasma osmolality by freezing point depression (Fiske Micro-osmometer, Model 210, Norwood, MA).

Heat exposures occurred in an environmental chamber set to 50°C, 20%rh where three cycles of 30-min treadmill walking (3.5 mph, 3.5% grade) and 30-min of rest (sitting) were repeated (total 3-h exposure). The purpose of the walking exercise was to increase body heat storage and induce sweating. The method of dehydration selected was considered the most appropriate as it is a legal means of losing mass in sport (Williams 1998), it is practical (i.e., sauna-like) and it produces a predictable hypertonic state within the intravascular fluid space (Feig and McCurdy 1977). Water loss was determined from changes in body mass measured every 30-min. Under the conditions tested, water (sweat, urine) volume and body mass losses were considered equivalent. The objective was to lose 4% of body mass, which would theoretically improve jump height also by 4% if work done by the leg muscles remained constant (Appendix). In EUH, volunteers drank 1 ml of 0.05% NaCl–water solution to replace every 1 g of lost mass. In HYP, no fluid was provided. A 45–90-min break followed heat exposure where volunteers showered and relaxed in a temperate environment (20–22°C). The purpose of this break was to allow core temperature to return to resting pre-heat exposure levels (Cheuvront et al. 2006). Importantly, the recovery period remained constant within-subjects. Following the break, nude body mass was again measured and this value was compared to the pre-heat exposure value. If body mass was less than the value measured prior to heat exposure, additional fluid was provided.

Following the 45–90-min recovery, warm-up and jump testing commenced as described in "Preliminary testing". The best of three vertical jump heights determined from the force platform was recorded in the same manner as preliminary testing. Within the HYP trial, volunteers performed three jumps with (HYP_v) and without (HYP) a weighted vest (Uni-Vest, Pittsburgh, PA) that replaced the mass lost from sweating. The vest itself weighed 0.60 kg and was designed to hold as many as 20 flexible weights which ranged from 219 to 226 g each. This allowed matching the mass of the weighted vest to the dehydration mass losses with ±100 g precision. Weight placement in the vest was divided equally between the dorsal and caudal torso and ergonomically aligned between the xiphoid process and navel to approximate the body center of mass. Like trials EUH and HYP, the order of jumps performed within HYP and HYP_v was counterbalanced.

Statistical analysis

The effect of treatment (EUH, HYP, HYP_v) on jump performance parameters was determined using a one-way repeated measures ANOVA. After a significant F test, Dunnett's post hoc test was used to compare HYP and HYP_v against EUH (control). The practical importance of differences in jump height between EUH and other trials was examined by comparing the mean and 95% confidence limits of the percent differences against a pre-specified zone of indifference (Cheuvront et al. 2005). This procedure is a corollary for significance testing which provides insight into the magnitude and uncertainty of the true (population) effect (Hopkins 2004; Nakagawa and Cuthill 2007; Reichardt and Gollob 1997). It is also similar to equivalence testing as it affords an evaluation of performance against an evidentiary standard other than zero (Batterham and Hopkins 2005; Ebbutt and Frith 1998; Hopkins 2004). The pre-specified zone of indifference, or trivial effect, in this study was the typical within-subjects jump height variability of 3.5%. This value is nearly identical to the vertical jump height CV of 3.6% reported by Viitasalo et al. (1987) for athletes accustomed to participating in sports that focus or rely heavily upon jumping. Conventional 95% confidence limits of a mean difference are statistically significant when they exclude the null value (zero). However, the relevance of either bound of the confidence interval must also be considered (Curran-Everett and Benos 2004). In this study, the practical importance of any significant difference was considered unequivocal only when the majority of the 95% confidence interval was outside the zone of indifference.

Sample size was calculated for comparisons of jump height, which was the central performance parameter of interest in this study. Applying conventional $\alpha = 0.05$ and $\beta = 0.20$ values, eight subjects were estimated to provide sufficient power to detect a 4% jump height difference from EUH (Appendix) using the mean jump height (0.370 ± 0.050 m) achieved during the initial 2 weeks of familiarization training coupled to the within-subjects CV (i.e., 3.5%) for an estimated effect size >1.0. However, because experimental perturbations produce unique performance infidelity (Hopkins et al. 1999), increase the observed CV, and decrease the anticipated signal-to-noise ratio, a sample size of 15 volunteers was tested to allow detection of desired differences with an effect size as small as 0.50 after adjusting for repeated measures (Lipsey 1990). All data are presented as mean ± SD except where indicated.

Results

Hydration

In all volunteers, the daily body mass variation (CV) after an overnight fluid bolus (30 ml/kg) was 0.6 ± 0.2%, similar to what has been reported previously when fluid intake was controlled (Cheuvront et al. 2004). Body mass upon arrival to the laboratory for testing (83.8 ± 10.9 kg) was within ±1% of the multi-morning average in all volunteers. The corresponding plasma osmolality was <290 mmol/kg (289 ± 4 mmol/kg) for the subset of 10 volunteers providing blood samples. Thus, all subjects were considered EUH at the start of each trial (Sawka et al. 2007). In trial EUH, fluid intake was sufficient to restore water losses during heat exposure, thus body mass was unchanged and plasma osmolality remained <290 mmol/kg (286 ± 4 mmol/kg). In trial HYP, body mass was reduced by 3.2 ± 0.5 kg (−3.8 ± 0.6%; $P < 0.05$) to 80.6 ± 10.3 kg and plasma osmolality increased to 300 ± 5 mmol/kg ($P < 0.05$). Body mass was restored to EUH values of 84.0 ± 10.6 kg (0.3 ± 0.5%) in HYP_v by adding back the mass lost (3.4 ± 0.5 kg) using the weighted vest. The recovery period (45–90 min) from heat stress was considered sufficient to return core temperatures to near resting levels (Cheuvront et al. 2006), though they were not measured. Importantly, the small obligatory elevation in core temperature typically produced by hypohydration (≤0.50°C) does not impact power performance outcomes (Cheuvront et al. 2006) and should not affect anaerobic chemo-mechanical energy conversions (Bennett 1984; Bosco et al. 1983). Any modest level of hyperthermia would also have been identical for comparisons between trials HYP and HYP_v.

Jump height and biomechanical performance parameters

Table 1 provides absolute (N) and relative (N/kg) force as well as absolute (W) and relative (W/kg) power measurements for the three experimental trials. Although no significant differences were observed for peak values during the dynamic motion phase of the measurement, qualitative trends indicate that the lowest absolute (N) and highest relative (N/kg) force measurements occurred in trial HYP, consistent with the effect of body mass manipulation on force production. Max power (W, W/kg) was lowest in HYP_v. Jump height (Table 2) was not different between EUH and HYP, but was 4% lower ($P < 0.05$) in HYP_v than EUH. Jump height was significantly reduced in HYP_v as a direct result of a reduced jump takeoff velocity (Table 2). A smaller ($P < 0.05$) VGRI was calculated for both HYP_v and HYP, which were 2–3% less than EUH (Table 2).

Figure 1 presents the percent change in jump performance from EUH. The percent change was significantly different for HYP_v but not for HYP. The means and 95% confidence intervals [HYP_v: −4% (−1.8 to −6.2%) and HYP: 1% (−1.6 to 3.4%)] provide the likely range of the true change effects and illustrate why there is a difference between EUH versus HYP_v but not between EUH versus HYP (i.e., when confidence interval crosses zero, $P > 0.05$). In addition, almost the entire confidence interval in EUH versus HYP falls within the training CV, while the majority of the confidence interval in EUH versus HYP_v is outside the same zone. This indicates that the significant reduction in jump performance in HYP_v is of sufficient magnitude to be considered important. Consideration was also given to a trial order effect, but no effect of trial order was found. In absolute terms, 12 of the 15 subjects performed worse in HYP_v while only 6 of 15 performed worse in HYP only (Fig. 2), the latter of which is consistent with chance. When comparing the theoretical improvement in jump height (Appendix) to the actual jump height in HYP (Fig. 2), 11 of 15 subjects failed to jump as high as predicted (Appendix).

Table 1 Absolute and relative measures of force and power during vertical jump testing

Trial	Max force		Max power	
	N	N/kg	W	W/kg
EUH	1766 ± 281	21.04 ± 1.75	3972 ± 558	47.48 ± 4.70
HYP_v	1761 ± 283	20.92 ± 1.74	3902 ± 590	46.54 ± 5.29
HYP	1721 ± 267	21.35 ± 2.13	3930 ± 564	48.85 ± 5.12

All data represent instantaneous maximums calculated during dynamic motion

Table 2 Performance parameters during vertical jump testing

Trial	Jump height (m)	Jump velocity (m/s)	VGRI (N s)
EUH	0.380 ± 0.048	2.73 ± 0.17	228.3 ± 30.3
HYP_v	0.365 ± 0.052*	2.67 ± 0.19*	224.3 ± 31.8*
HYP	0.384 ± 0.050	2.74 ± 0.19	220.6 ± 29.7*

* $P < 0.05$ from EUH

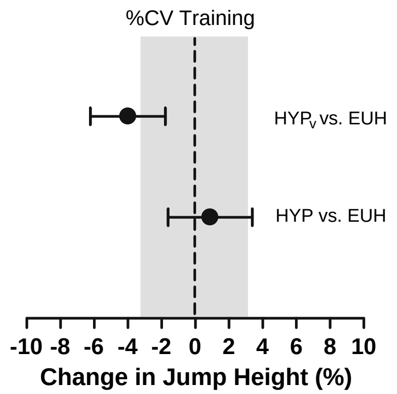

Fig. 1 Percent change in performance from EUH for both HYP and HYP$_v$ trials. Data are means; *bars* are 95% confidence intervals. *Shaded area* represents zone of indifference (±3.5%) based on the typical performance variability measured during practice sessions and a theoretical improvement in performance (~4%) in excess of the CV (see text and Appendix for details)

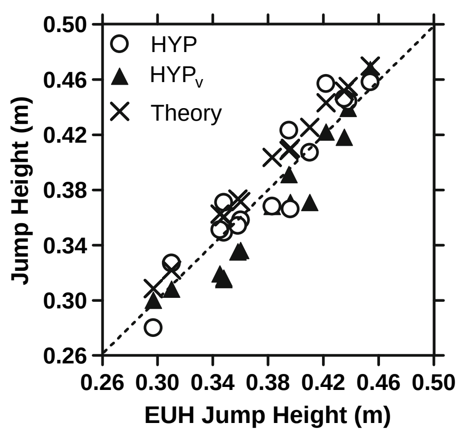

Fig. 2 Hypohydrated jump height (*y*-axis) plotted as a function of euhydration jump height (*x*-axis). *Dotted line* represents the line of identity, where values falling above or below the line are higher or lower jump heights than euhydration, respectively. Values denoted by 'X' represent the theoretical improvement in jump height attributable solely to a lighter body mass (see Appendix for details)

Discussion

This was the first study to examine the impact of hypohydration on jump performance using sophisticated biomechanical measures from a force plate, while holding mass constant in the S/M, thus enabling examination of the biomechanical trade-offs between mass loss and the potential consequences of hypohydration on functional leg strength (Aagaard et al. 2002; Cordova and Armstrong 1996) during a vertical jump. The principle findings of this study were: (1) hypohydration impaired VGRI; (2) when body mass was equated with trial EUH using a weighted vest (HYP$_v$), jump height was significantly reduced by hypohydration; (3) a lower body mass in HYP did not significantly improve jump height as predicted by standard physical laws (Appendix), apparently due to offsetting S/M changes.

The finding that EUH and HYP jump heights were not different is consistent with other studies evaluating the impact of hypohydration on jump performance (Gutierrez et al. 2003; Hayes and Morse 2009; Hoffman et al. 1995; Judelson et al. 2007b; Viitasalo et al. 1987; Watson et al. 2005). The finding that HYP$_v$ jump performance was less than EUH seems to contradict Viitasalo et al. (1987) who observed no effects of hypohydration on jump performance with barbell loads of 20–80 kg. Though the subject population (athletes accustomed to jumping) might explain differences in performance susceptibility to hypohydration (Hakkinen et al. 1984), substantial barbell loads would alter stored elastic energy (Hakkinen et al. 1984) and jump biomechanics far more and presumably renders obsolete direct comparisons to an ergonomically weighted 3.4 kg vest. The importance of the HYP$_v$ performance effect magnitude is evidenced by the fact that the majority of the confidence interval for the percent change in jump height lies outside the typical noise of the measurement, while performance in HYP lies almost entirely within it (Fig. 1). The traditional use of 95% confidence intervals applied to a 3.5% CV evidentiary standard can even be viewed as conservative (Hopkins 2004; Hopkins et al. 1999), thus strengthening our interpretation of importance. By virtue of comparison, it requires 8 days of chronic activity, sleep deprivation, and underfeeding to achieve the same ~4% decrement in jump performance (Welsh et al. 2008) achieved herein with a -3.2 ± 0.5 kg (-3.8 ± 0.6%) total body water deficit.

Measures of force and mass can explain both the preservation of jump height in HYP and the decrement observed in HYP$_v$. Peak force measures were not different among the three trials (Table 1), but vertical jump height is maximized by a delicate balance between peak force and kinetic impulse (force × time) (Cordova and Armstrong 1996; Harman et al. 1990). The product of applied force and time during the propulsion phase of jumping, or the VGRI, is equivalent to the change in momentum (mass × velocity) of the TBCM (Cordova and Armstrong 1996; Harman et al. 1990). Despite a lower VGRI, HYP jump velocity and jump height were preserved (Table 2). This appears to be explained by a proportional decrease in body mass in HYP, since the similar reduction in kinetic impulse in HYP$_v$ impaired jump velocity and jump height when body mass was the same as EUH. Furthermore, the lower body mass in HYP did not confer the expected vertical jump advantage predicted by a ~4% lower body mass (Appendix). Thus, the lower jump height in HYP$_v$, coupled with the reduced VGRI in both HYP and HYP$_v$, reveals that the pernicious consequences of hypohydration on jump height are observable only when mass is held constant.

The physiological mechanism(s) by which hypohydration might impair the potential for improving vertical jump at a reduced body mass are not clear. There is little support for postulating that hypohydration changes metabolic energy stores (ATP/PC) (Montain et al. 1998), physiological buffering capacity (Bigard et al. 2001), alterations in muscle membrane excitability (Costill et al. 1976), thermal influences on muscle function/elastic energy (Bennett 1984), or any other aspect of intra–extracellular muscle compartment changes (Evetovich et al. 2002). The inability to improve vertical jump height in trial HYP and the decrement in jump height observed in trial HYP_v might have motoneural underpinnings (Aagaard et al. 2002; Enoka and Stuart 1992) possibly related to the high osmotic stress created by hypohydration (300 mmol/kg) (Boulant and Silva 1988; Kraemer et al. 2001; Rapoport 2000). Alternatively, unpleasant sensations related to hypohydration, such as headache, lightheadedness or malaise, could also reduce motivation mediated motoneural firing (Enoka and Stuart 1992). Though the precise mechanism(s) or sensory pathways that would implicate 'central fatigue' (Enoka and Stuart 1992; Gandevia 2001) in reducing VGRI in both HYP and HYP_v cannot be gleaned from the data at hand, the fact that VGRI was reduced similarly in both HYP and HYP_v (Table 2) suggests a physiological, rather than mechanical (weight bearing), explanation for the lower jump height in HYP_v.

Conclusions

Hypohydration has no apparent net effect on jump height due to offsetting reductions in VGRI and body mass. However, VGRI, jump velocity, and vertical jump height were all reduced when lost water mass was replaced with a weighted vest, indicating genuine performance impairment with hypohydration otherwise masked by alterations in the S/M. It is, therefore, plausible that hypohydration will have negative, but difficult to observe, effects on performance in sports or occupations where the S/M is important (e.g., Judelson et al. 2007a; Kraemer et al. 2001; Welsh et al. 2008).

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Appendix

Summary of calculation for theoretical jump height[1] improvement with hypohydration:

$$\text{force}_1 \times \text{distance}_1 = \text{force}_2 \times \text{distance}_2$$
$$\text{body weight}_1 \times \text{jump height}_1 = \text{body weight}_2 \times \text{jump height}_2$$
$$\text{jump height}_2 / \text{jump height}_1 = \text{body weight}_1 / \text{body weight}_2$$
$$\text{jump height}_2 = \text{jump height}_1 \times (\text{body weight}_1 / \text{body weight}_2)$$

where

body weight_1 = body weight before hypohydration
body weight_2 = body weight after hypohydration
jump height_1 = jump height before hypohydration
jump height_2 = jump height after hypohydration

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[1] Assumes work (force × distance) is unchanged by hypohydration, rather than impulse (force × time) (Viitasalo et al. 1987), since a lighter body mass would be accelerated faster if force remained constant, thereby reducing impulse by shortening the time of force application. As a result, the level of hypohydration (e.g., 4%) is equivalent to the theoretical percent improvement in jump height. [Note: If impulse remained constant, the denominator of the equation above would become squared and the theoretical improvement would be double the level of hypohydration (e.g., 8%).]

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